Laser plasma accelerator based collider R&D “roadmap”

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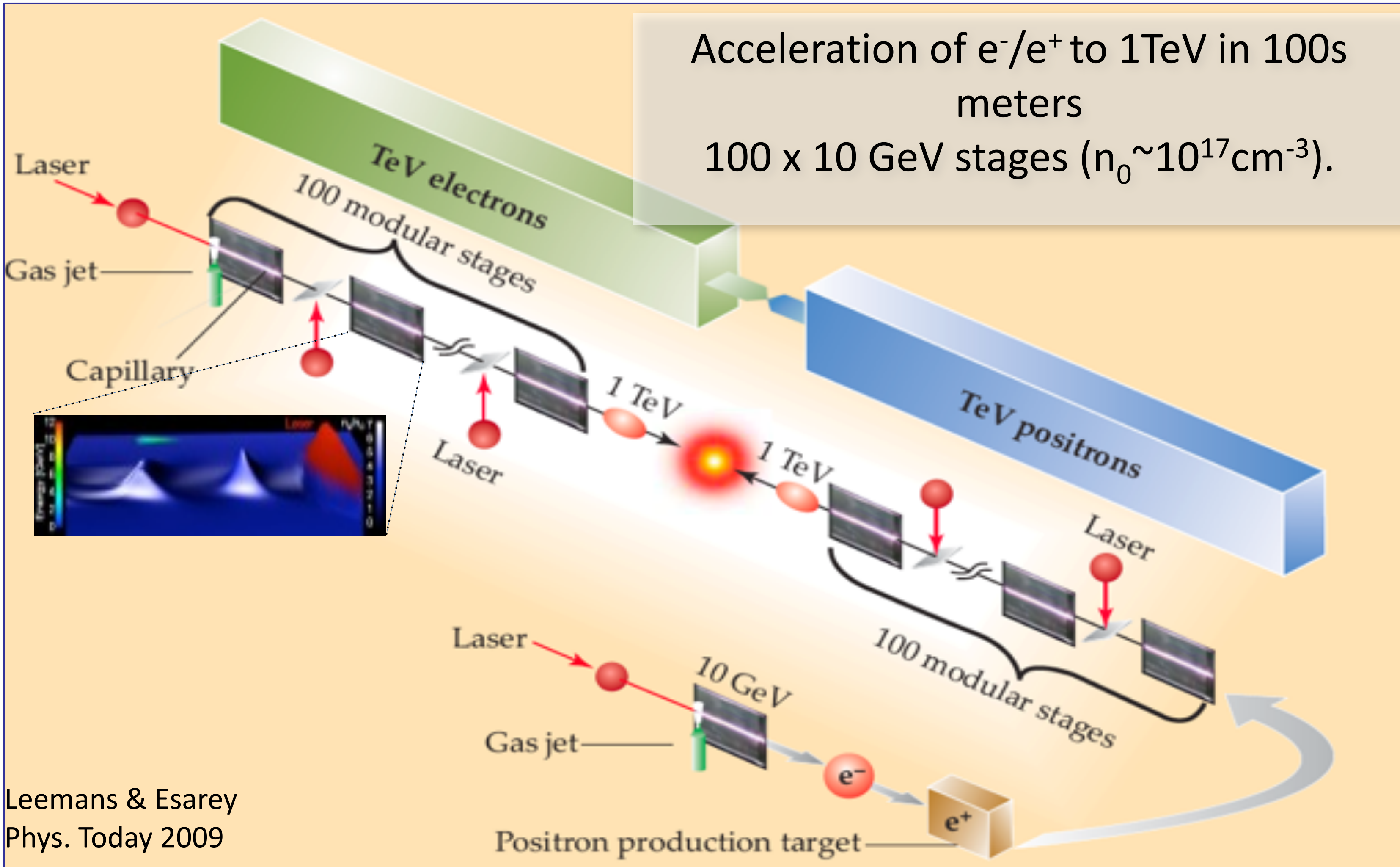
Contract DE-AC02-05CH11231

A vision for a future laser plasma accelerator based collider



Acceleration of e^-/e^+ to 1TeV in 100s meters

100 x 10 GeV stages (n_0~$10^{17}cm^{-3}$).

Leemans & Esarey
Phys. Today 2009

- We next discuss the R&D that is needed to address key feasibility questions

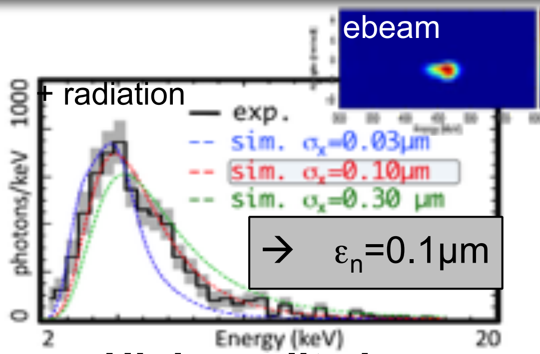
R&D Topics for Laser Plasma Linear Collider (LPLC)

- **Path to higher-energy using laser-plasma accelerators (LPAs)**:
  - High gradient requires high plasma density; Laser depletion at high density requires staging (coupling new laser into plasma structure)
    - ➡ *critical experiment*: demonstrate staged LPAs
- **Improved LPA efficiency** (laser-to-beam):
  - Laser to beam efficiency increased by tapering plasma density
    - ➡ *critical experiment*: taper density to phase-lock e-beam
- **Phase space quality and control**:
  - Independent control of focusing required for emittance control
    - ➡ *critical experiment*: demonstrate control of focusing forces in LPA using higher-order laser modes and tailored plasma ramps
- **Positron acceleration**: (requires operating in quasi-linear regime)
    - ➡ *critical experiment*: demonstrate e+ beam acceleration in LPA

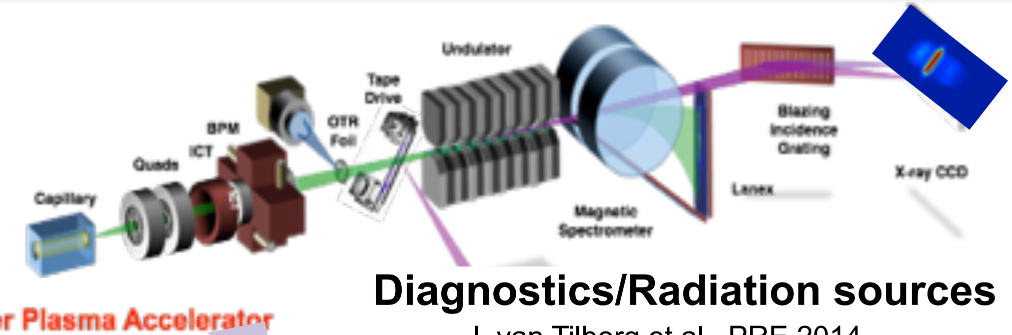
R&D Topics for Laser Plasma Linear Collider (LPLC) — continued

- **Beam cooling**:
  - Ultra-cold e-beam injection via plasma and/or laser tailoring
  - Compact cooling via plasma-wave-based radiation generation
- **Power handling inside plasma structures**:
  - Trade-off between efficiency and accelerating gradient
  - Plasma source design
  - Energy extraction methods (e.g., “clean-up” laser)
- **Spin polarization**:
  - Injection of spin-polarized e-beam sources into LPA
  - Survival of spin polarization in LPA
- **Final focus**:
  - gamma-gamma collider (laser technology development)
  - adiabatic plasma lens to reduce final focus length

LBNL Program focuses on science and technology for laser plasma accelerators and applications

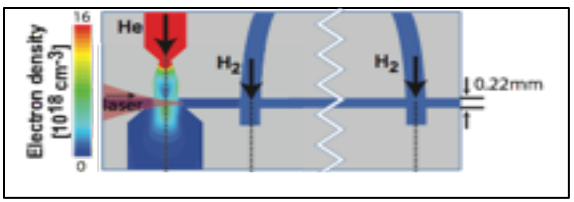


High quality beams

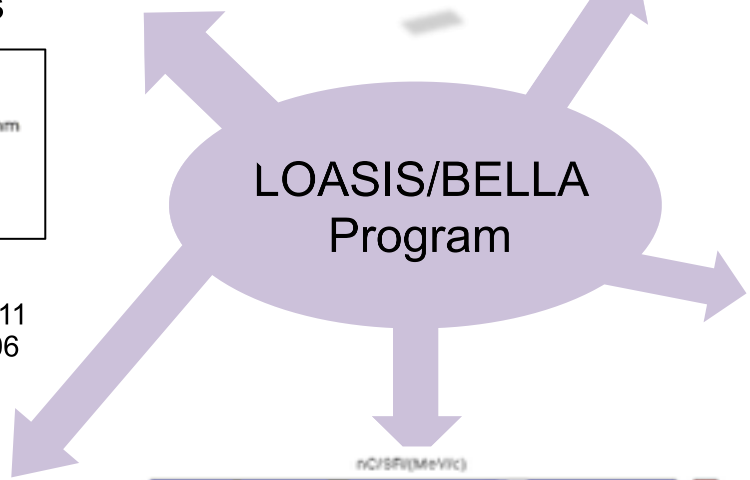


Diagnostics/Radiation sources

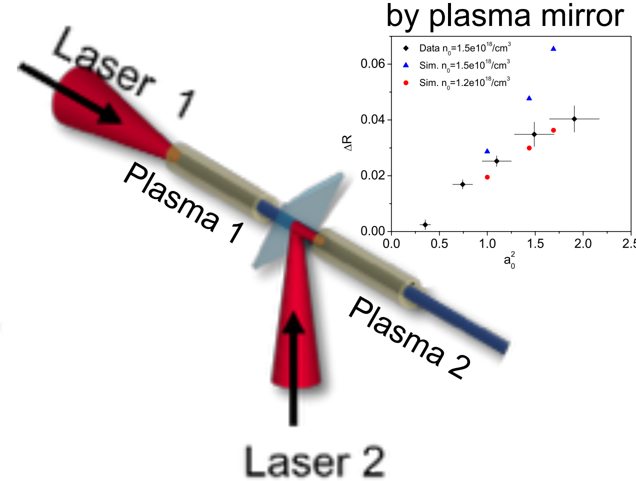
J. van Tilborg et al., PRE 2014
J. van Tilborg et al., Optics Lett 2013
B. Shaw et al., J. Applied Phys. 2013
L. Chen et al., PRL 2012

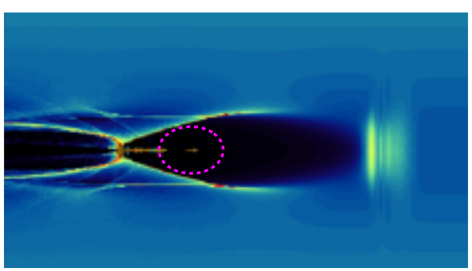


G. Plateau et al., PRL 2012
A.J. Gonsalves et al., Nature Phys. 2011
W.P. Leemans et al., Nature Phys. 2006
C.G.R. Geddes et al., Nature 2004



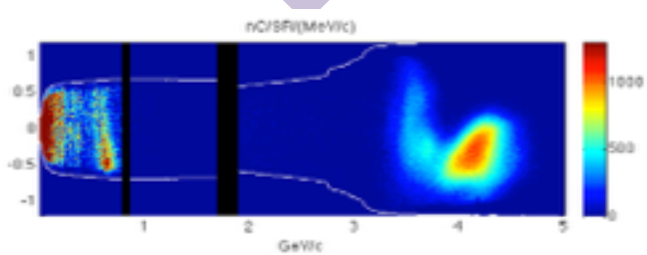
2[nd] stage powered by plasma mirror





Theory/Modeling

C. Benedetti et al., Phys. Plasmas 2014
L.L. Yu et al., PRL 2014
C.B. Schroeder et al., Phys. Plasmas 2013
C. Benedetti et al., Phys. Plasmas 2013



Multi-GeV beams

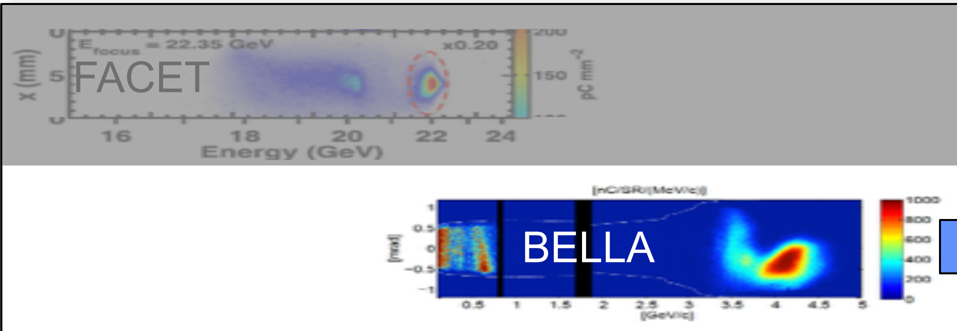
W.P. Leemans et al., submitted 2014
N. Bobrova et al., Phys. Plasmas 2013
C. Benedetti et al., Phys. Plasmas 2012

Staging, optimized structures

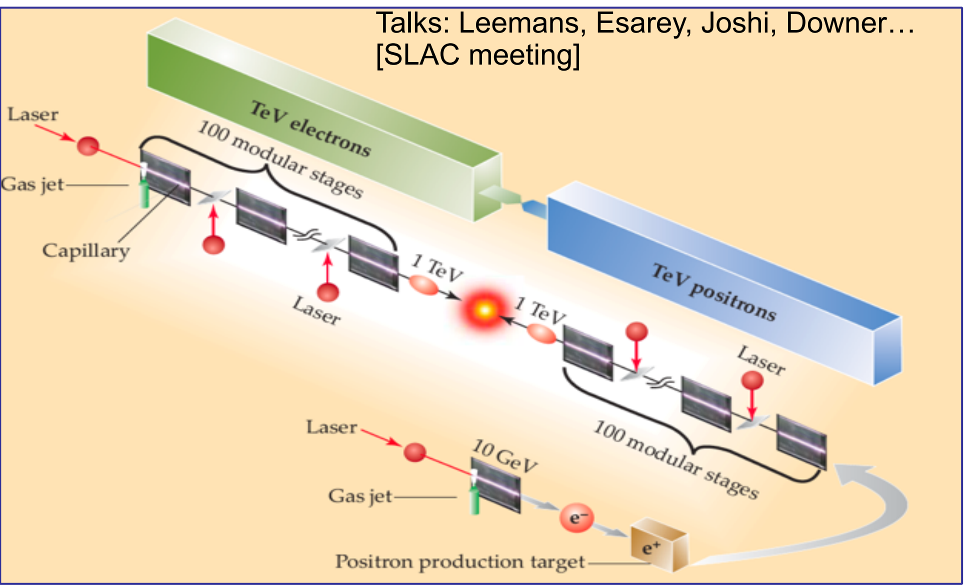
S. Shiraishi et al., Phys. Plasmas 2013

Future-generation accelerators at dramatically lower cost
Advances in modeling will offer new opportunities

Multi-GeV laser plasma accelerators



Laser-plasma (LPA) collider concept:
100x 10 GeV stages (1m ea.), injector, focus, e+



– Accelerator: EM + plasma + beam

	K-BELLA	Collider
3-D full PIC	$\sigma_{x,beam}$~1μm L_{acc}~1m	$\sigma_{x,beam}$~0.1μm L_{acc}~100m
Now Lab frame	~ 1year	~ 10^4 year
Now Boosted frame	~ 1hour parametric	~ 1 year
Goal 2024 Boosted frame	<1min real-time on	~ 3-4 days
Goal 2024 Boosted frame + AMR + env. 10^6 cores	<10ms real-time on clusters	~ 1 hour parametric studies on supercomputers

Advances in computers & algorithms:

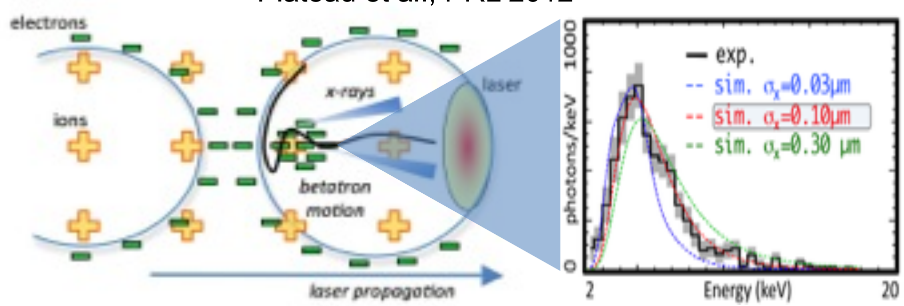
- real-time of single stages on clusters,
- design of colliders on supercomputers.

Controlled injection enables high quality beams

- Separate injector control from structure
  - Energy tuning & stability
  - Decrease ΔE
  - Lower emittance

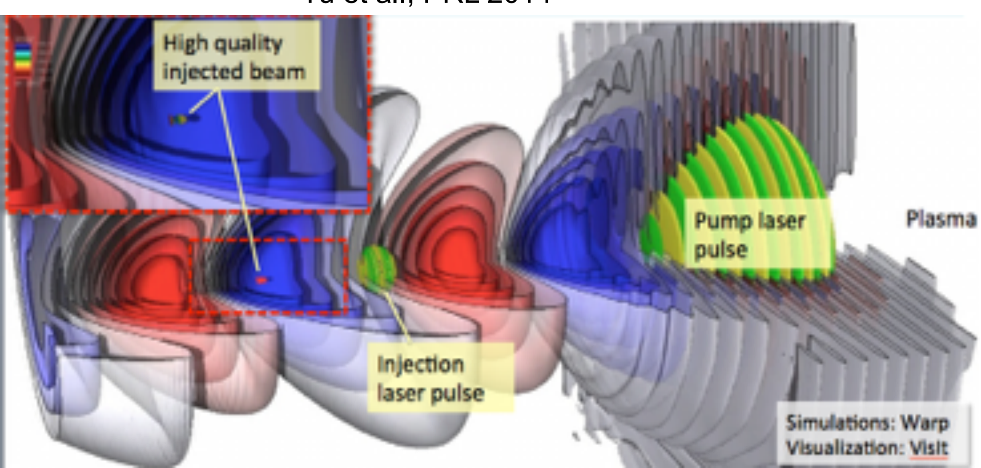
0.1 mm-mrad emittance: betatron radiation

Plateau et al., PRL 2012



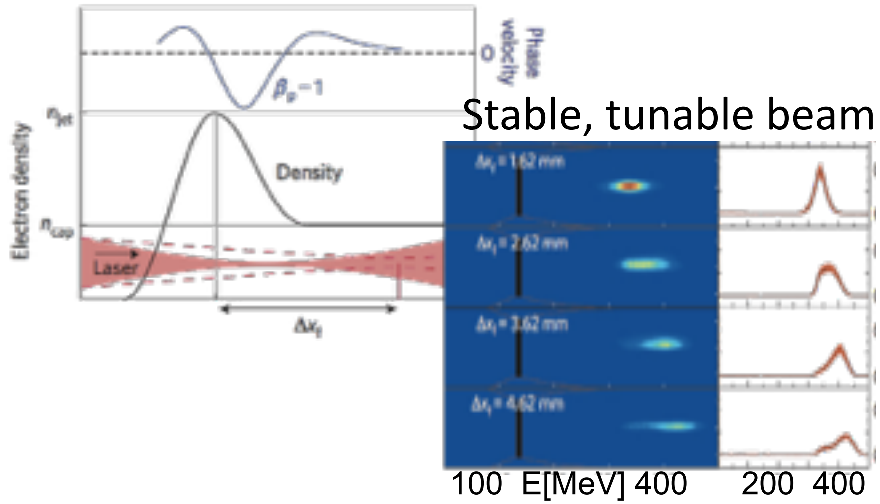
Advanced methods: 0.03 mm-mrad emittance

Yu et al., PRL 2014



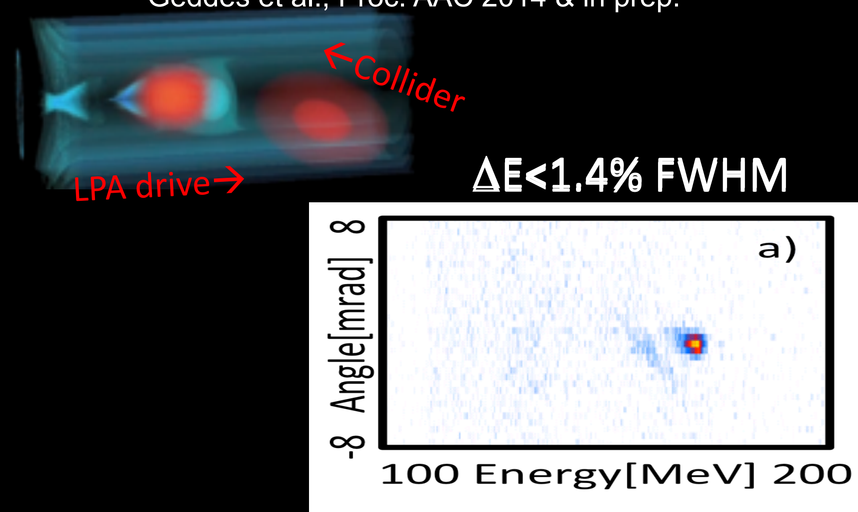
Tuning & stability: plasma down ramp

Gonsalves et al., Nature Physics 2011



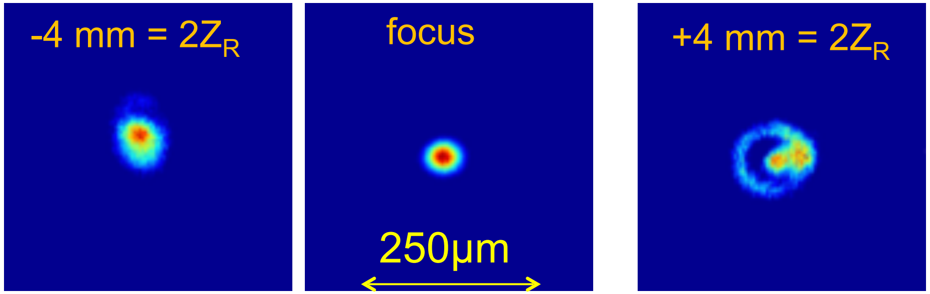
1% level energy spread: colliding laser pulses

Geddes et al., Proc. AAC 2014 & in prep.

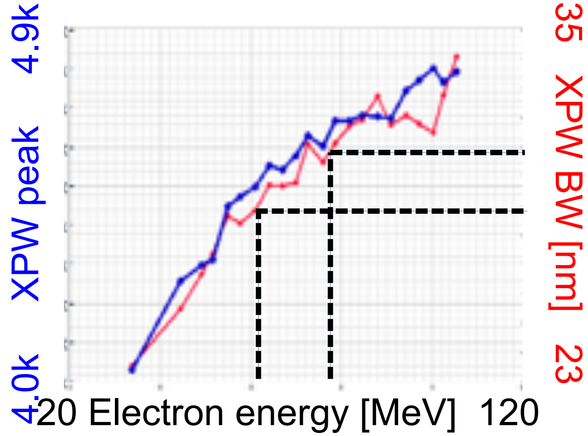


LPA as operational accelerator
Focused on stability for staging experiment's first stage

- Laser mode over full focal depth controls propagation



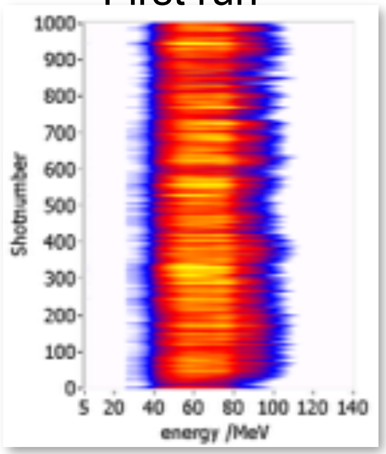
- Laser bandwidth/pulse shape controls stability



- Plasma target profile & stability control structure

Repeatable LPA over weeks of operation

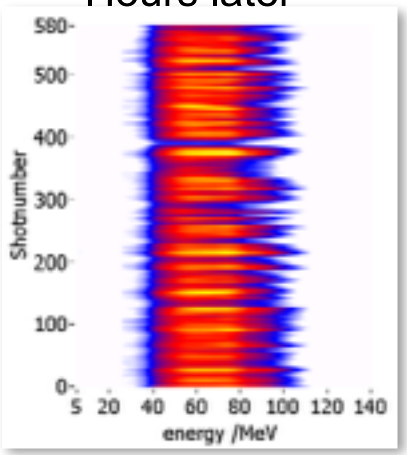
First run



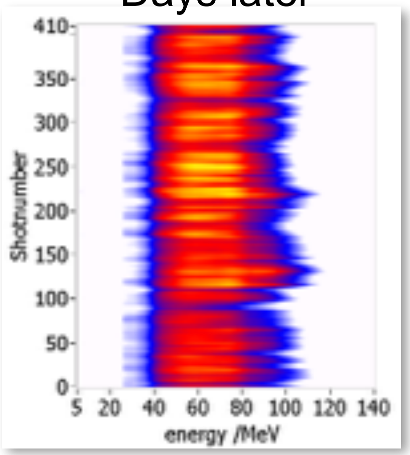
Pointing ±0.3 mrad

Diverg. FWHM 2.3±0.3 mrad

Hours later



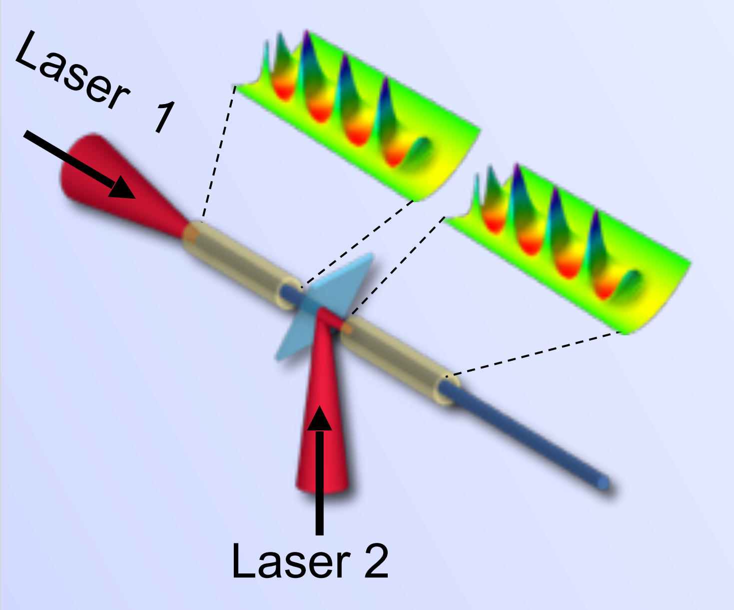
Days later



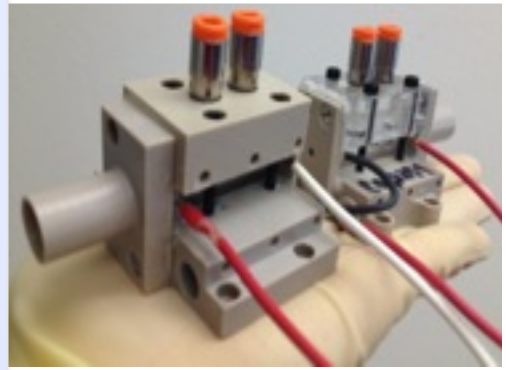
Steinke et al., Proc. AAC 2014

Staging setup was designed and installed 2009-2012 and first experiments were started in summer 2012

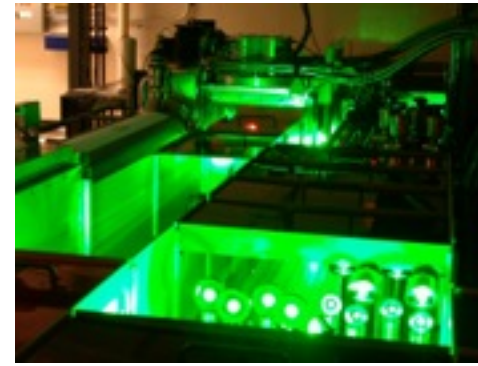
Staging concept



Staging capillaries



TREX laser

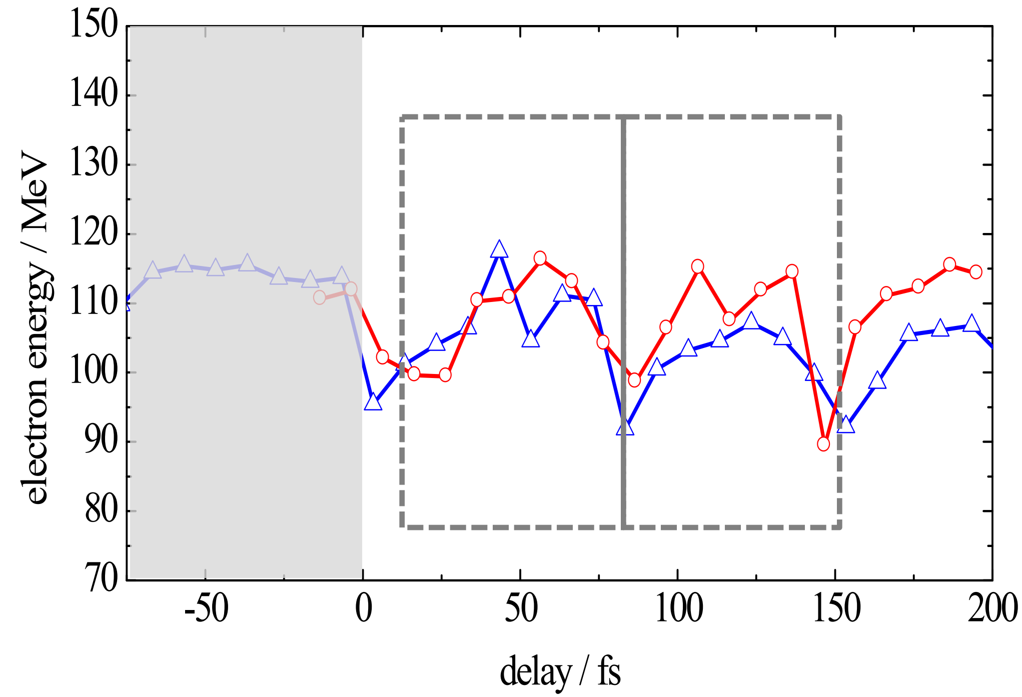


- S. Shiraishi graduated – postdoc at UCSD
- T. Sokollik (postdoc) – group leader in Shanghai

Electron beam dump | Electron spectrometer | High power laser diagnostics | Interaction chamber and beam transport chambers

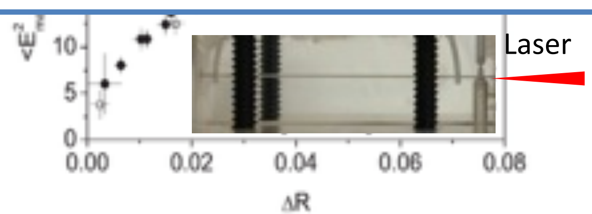
Staging experiment has progressed and first signatures of beam from first stage being affected by second stage have been observed

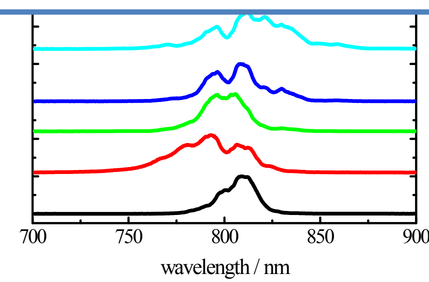
- Tape drive based plasma mirror characterized
- Gas jet density profile
- Injector stage characterized

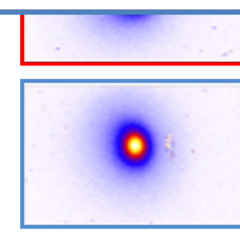


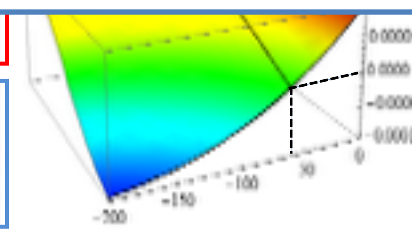
First delay scans reveal:

- Electron beam modulation depth of ~30 MeV
- Corresponds to interaction over Rayleigh length
- Modulation frequency $\sim\omega_p$





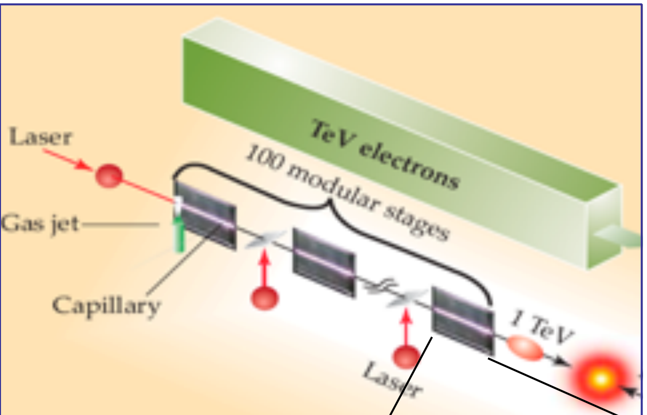




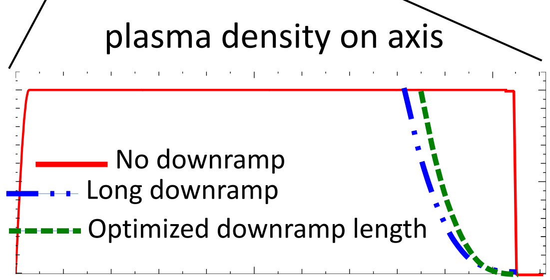
S. Shiraishi et al.

Multi-stage emittance control via tailored plasmas

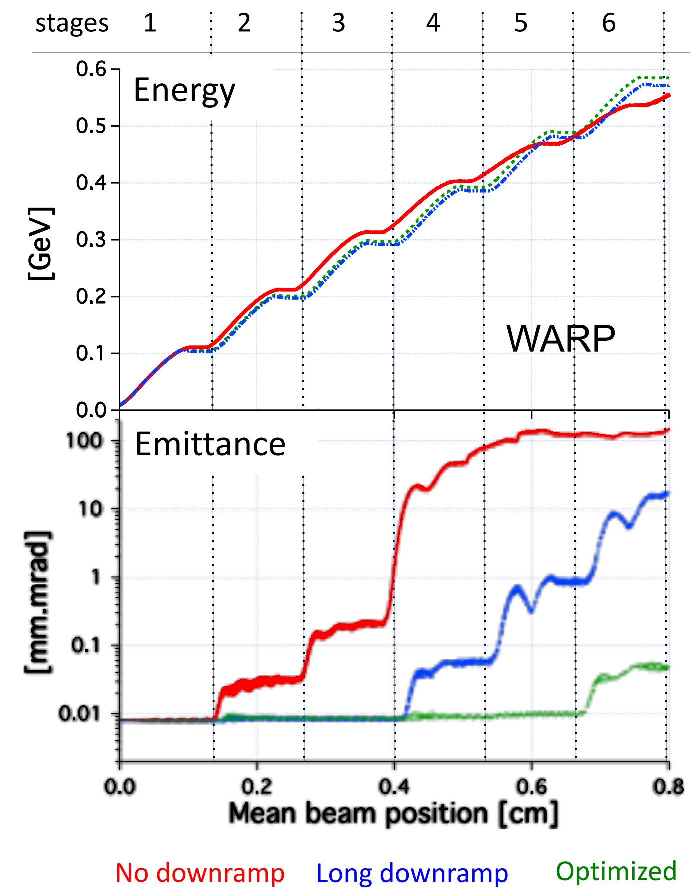
Match beam to each stage



Simulations of scaled 100 MeV stages (2-D Boosted frame)



Electron beam

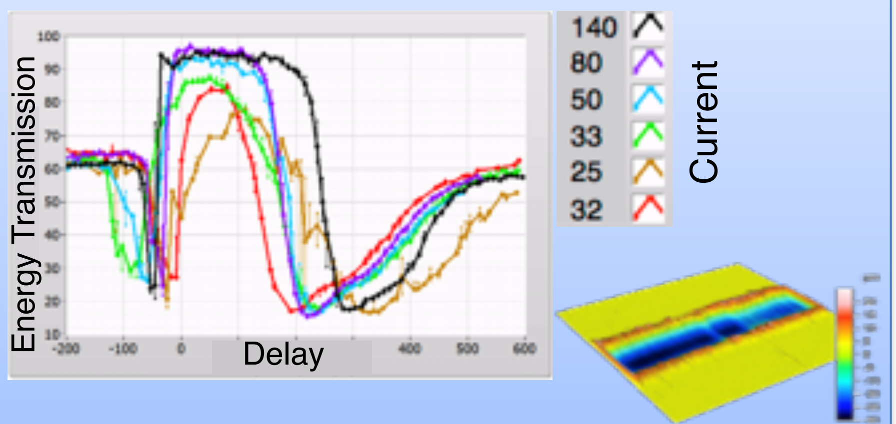


- Plasma density controls focusing force
- Densit ramp at exit controls Beam divergence /size
  - uniform ramp: low emittance growth for 5 stages
- Next: adjustment per stage and/or plasma lenses

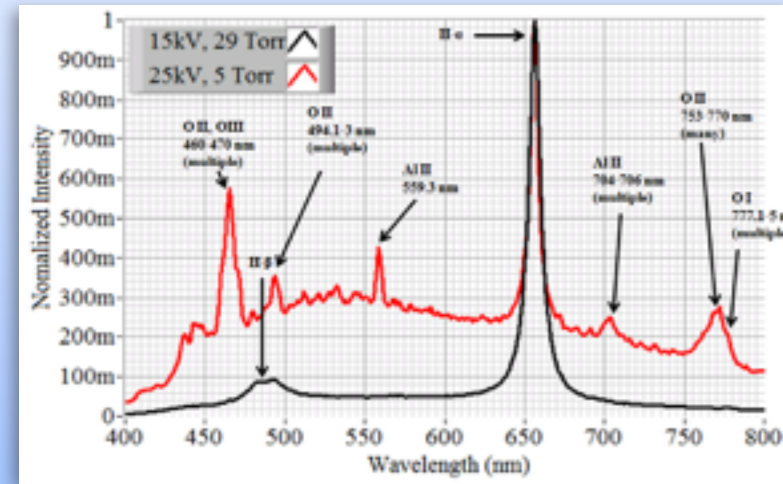
Vay et al., Proc. AAC 2014 & in prep.
Rykovanov et al., submitted to J. Phys. B

Significant progress made developing kHz plasma channel

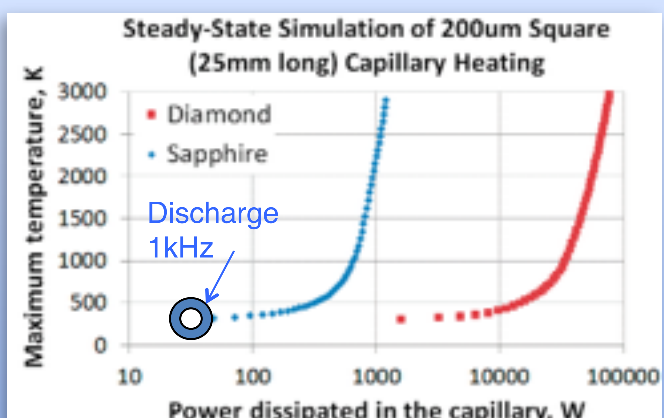
Single Shot erosion mitigated by current optimization and diamond capillaries



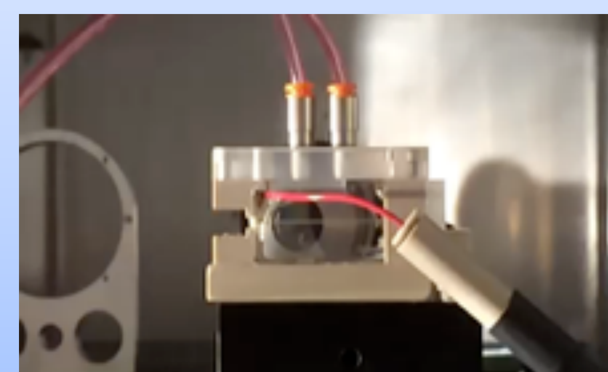
New diagnostics measure erosion and plasma temperature



Simulations show avg. power from discharge tolerated for >>kHz with water cooling. Energy recovery useful for LPA.

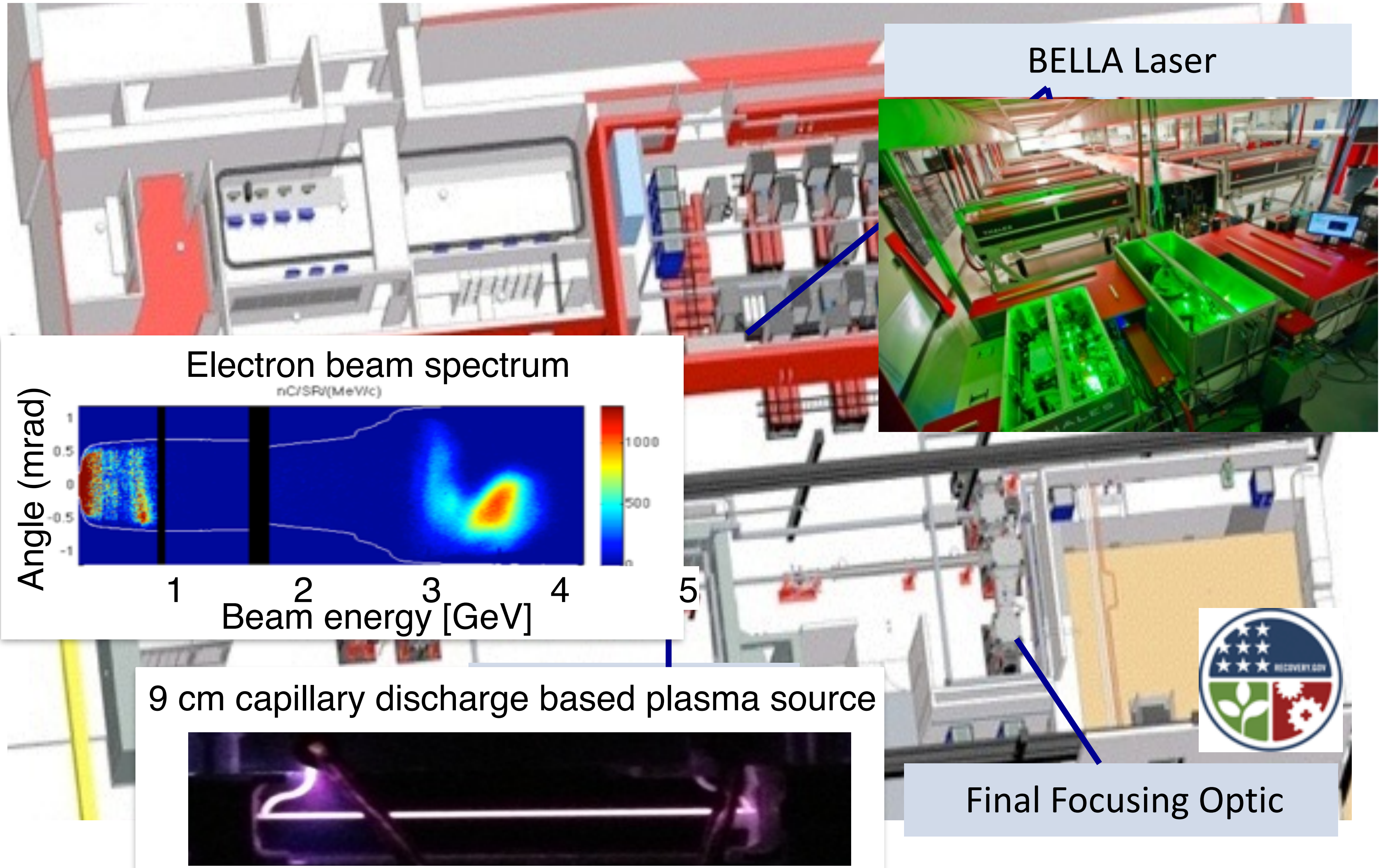


kHz pulser built and demonstrated discharge in bursts. Water cooling being implemented for continuous kHz

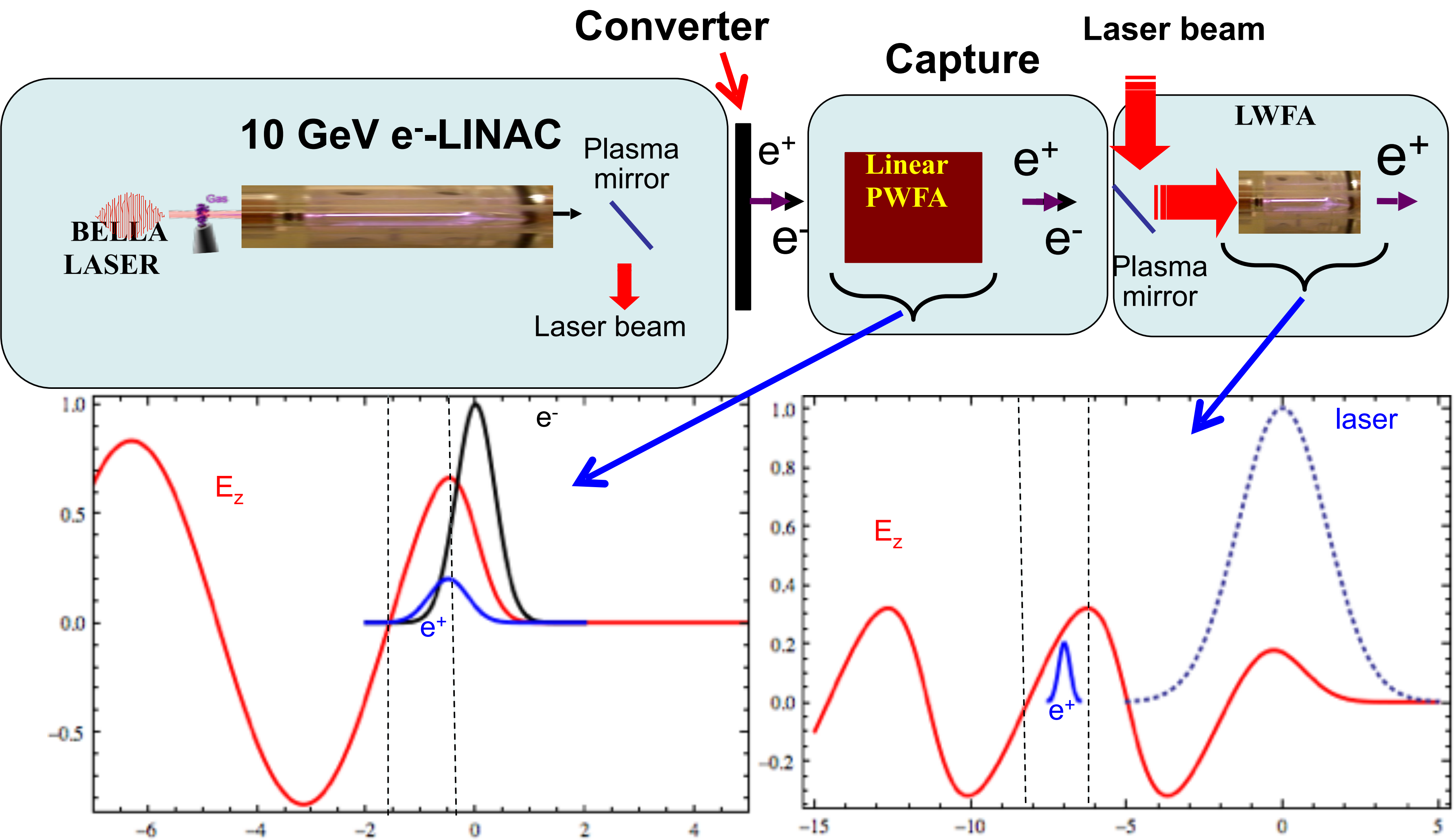


euclid

BELLA houses a state-of-the-art high repetition rate PW-laser for laser plasma accelerator science – demonstrator for 10 GeV



New concept for positron capture and acceleration could be pursued using multi-GeV e-beam from BELLA



Short to medium term R&D goals aim at addressing critical issues for LPA

Can we make LPAs sufficiently stable, tunable, controllable?
- Injection studies, emittance control, phase space studies
- Plasma source development (with industry)

Can we reach 10 GeV in a single stage and can we capture and accelerate positrons?
- BELLA experiments

Can we stage two or more modules?
- Staging experiment

Can we reach needed efficiency from laser to e-beam?
- Beam shaping for optimized beam loading (with CBP and others)

Can we operate the structures at high rep rate without damage?
- Understanding energy deposition and heat handling

Can we minimize scattering inside plasma and still maintain focusing forces?
- Near-hollow plasma channel concept

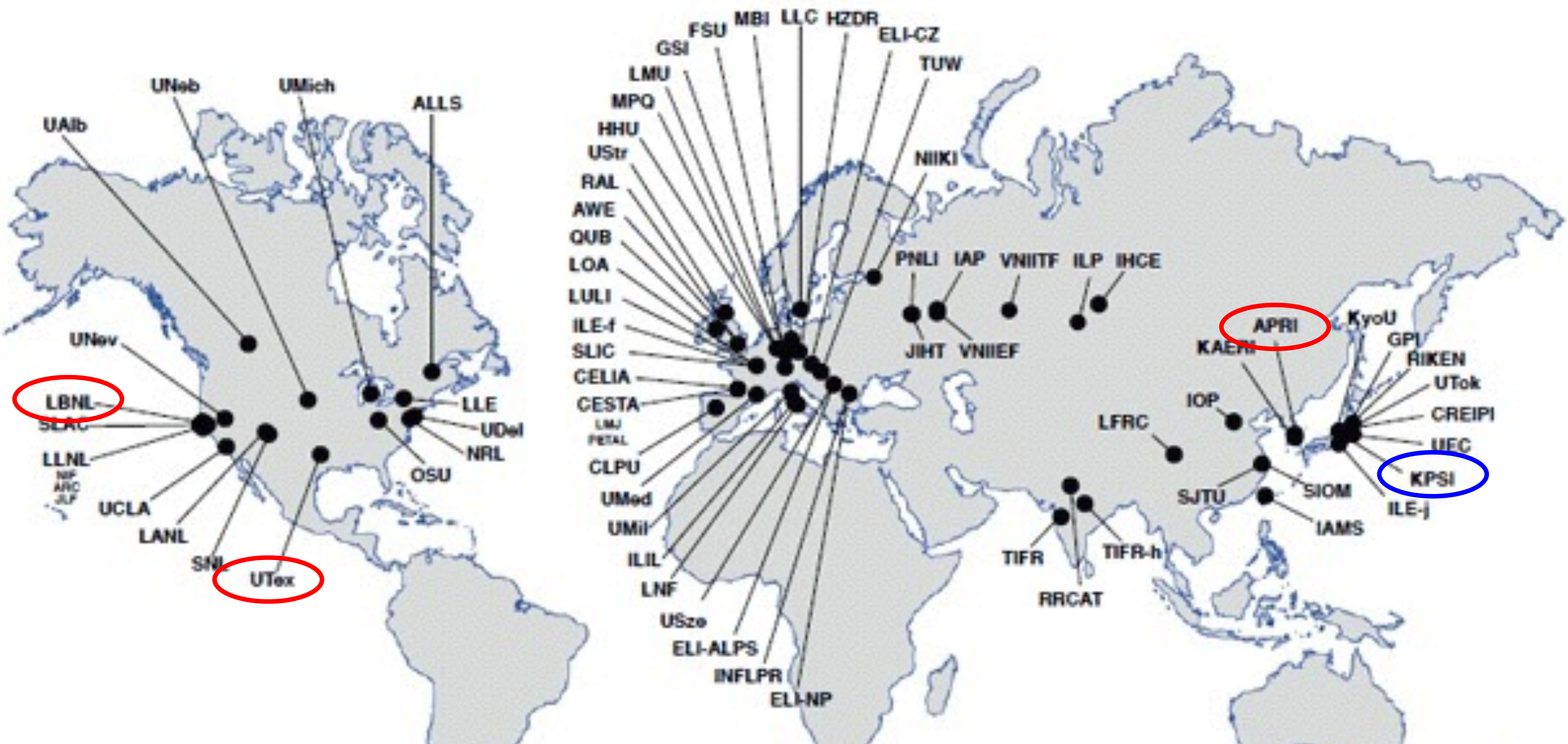
Are there concepts to simplify laser design?
- Incoherent combining of laser pulses to drive coherent wakes

How to measure the accelerator properties so that we can control the beams?
- Novel diagnostic developments

Resources are needed to maintain US competitiveness and leadership in laser plasma accelerator science

- European Extreme Light Infrastructure investment:
  - > $1 B from 2012-2017
- Comprehensive US program through critical investments:
  - BELLA: 2009-2012 -- ~$30 M investment
    - World record setting PW class laser at 1 Hz
    - First results: > 4.2 GeV from 9 cm structure
  - Maintain and grow current program of laser plasma accelerator science
    - Beam quality, staging, efficiency
  - New demonstrator investments:
    - BELLA-II: high average power demonstrator at kW-level
      - FY15-FY20, $30-35 M, requires development of new laser
      - Opens up near-term applications
    - BELLA-III: multi 10's of kW FY20-25, $50-100 M level
      - Full-scale demonstrator module for collider

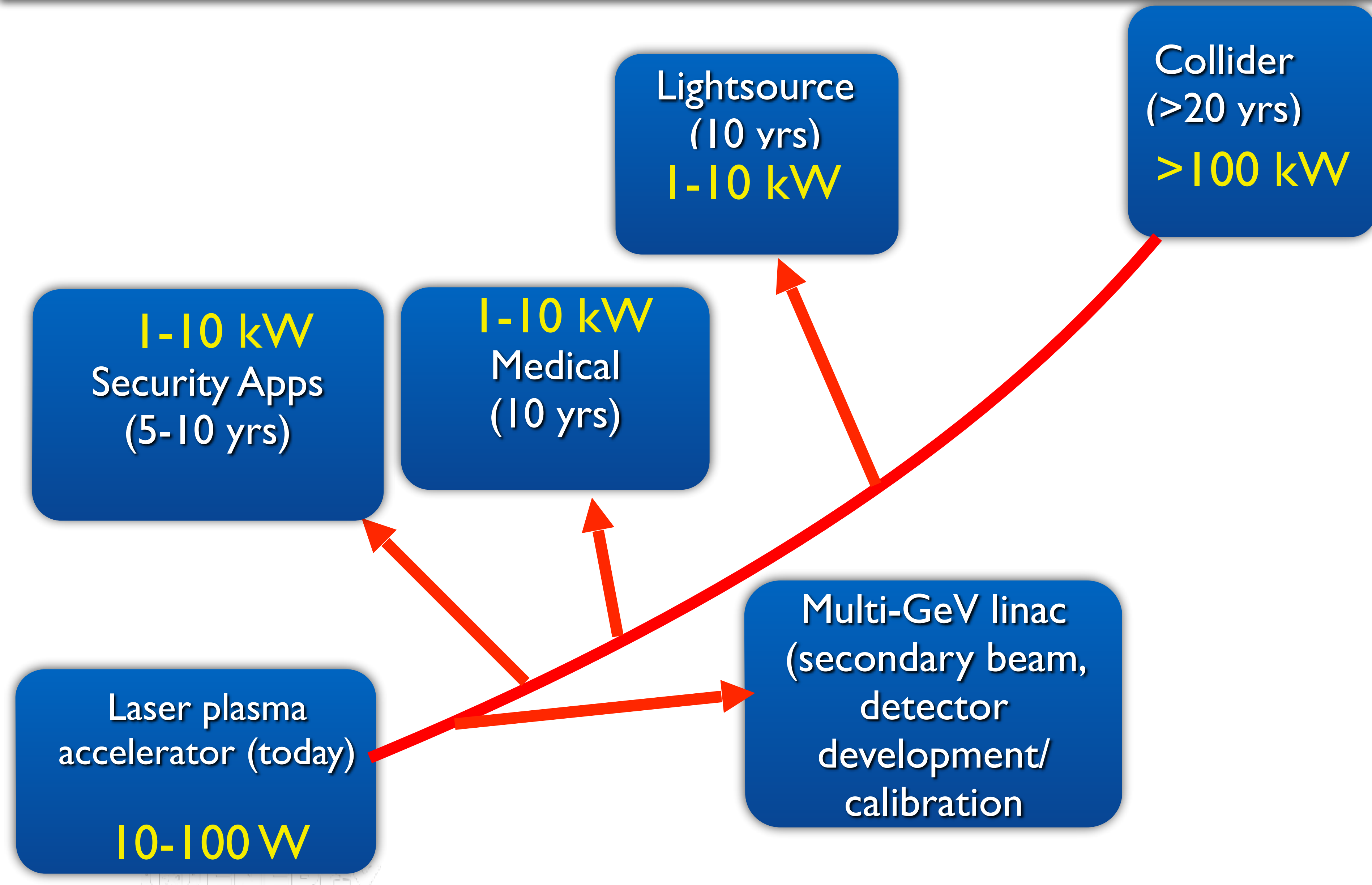
Petawatt class lasers becoming available with a ten fold expansion planned by 2017-2018 (mainly outside of USA)



- Total peak power of all CPA systems operating today is ~11.5 PW
- By 2018 planned CPA projects will bring total to ~ 127 PW
- Estimates do not include present MJ or planned Exawatt scale projects

Courtesy: C. Barty, LLNL

Many applications need higher average power



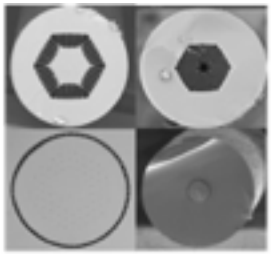
Applications using laser plasma accelerators require new laser technology to meet the demands on average power

BELLA Petawatt laser operates at “only” 40 W – we need multi-kW

- Launching new initiative to develop revolutionary new laser technology:
  - kW class, 100-200 TW laser at 1 kHz for driving high rep rate GeV laser plasma accelerator

- Aligned with new stewardship program in HEP
  - Exploring fiber based technology including coherent and incoherent combining

- Demonstrator for high average power laser plasma accelerator suitable for applications

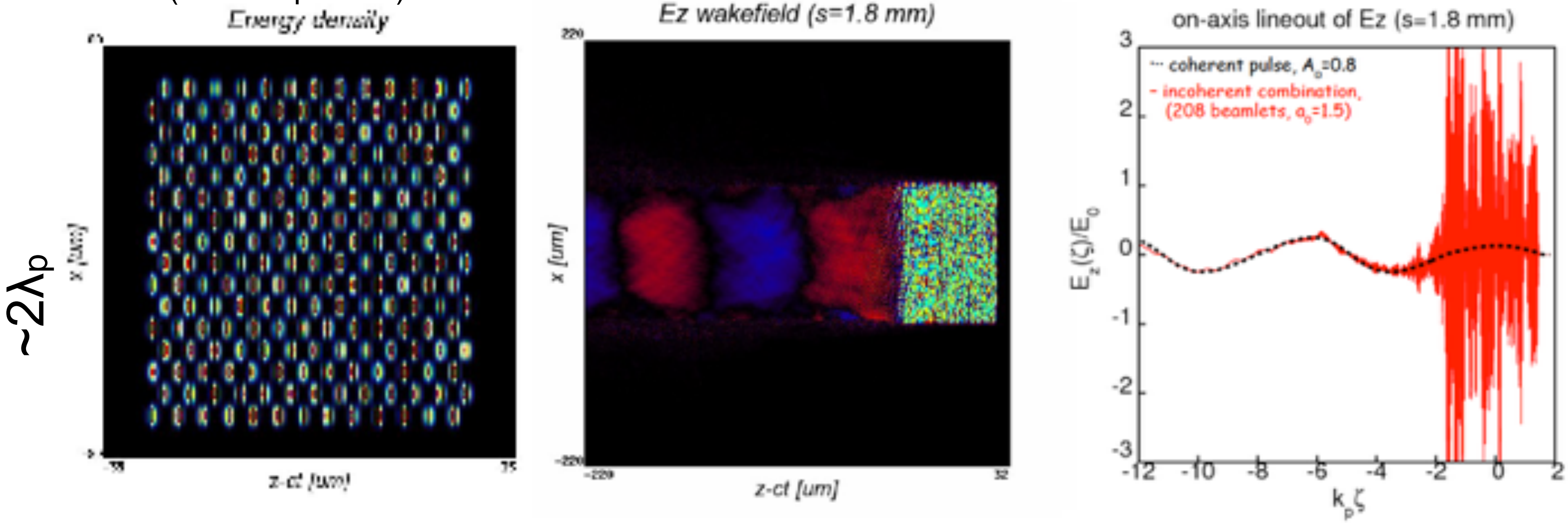


Novel fiber designs, PCF

A new concept has emerged that could radically change requirements on lasers

- Plasma wave excitation by incoherent laser pulses: path to high-average and high-peak power lasers for LPA
  - Analysis of wakefield excitation by incoherent laser pulses
    - Benedetti et al., Nature Photonics, (under review, 2014)
  - Guiding and combining multiple incoherent laser pulses
    - Benedetti et al., Phys. Plasmas (accepted, in press 2014)

208 laser beamlets
(random phases)

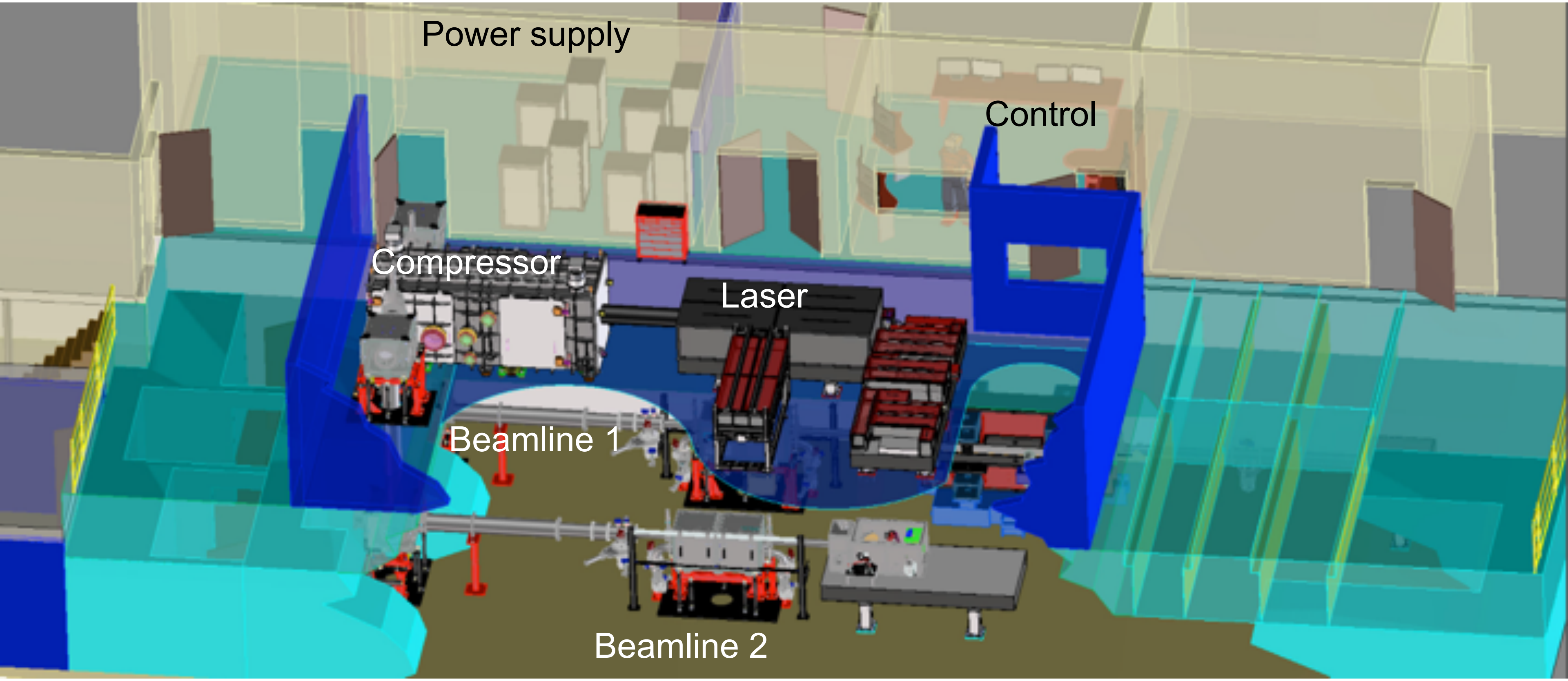


~λ_p /2

- Same integrated momentum gain for coherent pulse and incoherent combination
- Will have significant impact in thinking about future high average power lasers

k-BELLA (aka BELLA-II): Demonstrator for high average power LPAs

kHz, joule-class laser with two independently shielded beamlines

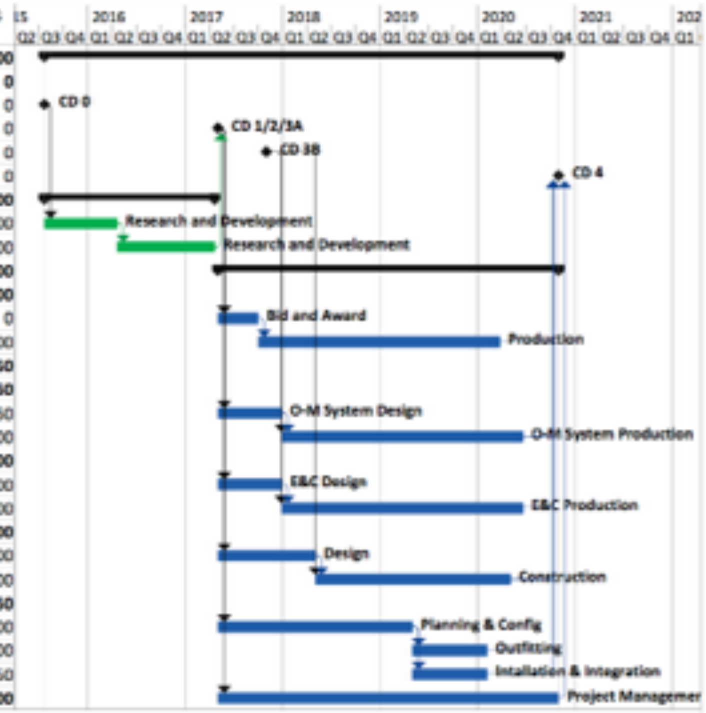


- High rep rate, high average power (1-3 kW) laser and high rep rate plasma targets
- Co-located with BELLA
- Two beam lines — user facility for high power laser driven accelerator concepts

k-BELLA project is modeled after successful BELLA project

BELLA: PW at 1 Hz; k-BELLA: 0.1 PW, kW high average power at kHz

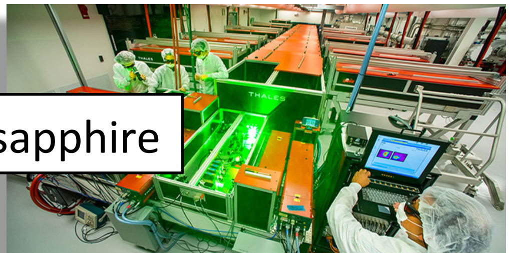
ID	Task Name	Start	Finish	Cost k$
1	BELLA II	4/22/15	7/30/20	37,000
2	Milestones	4/22/15	7/30/20	0
3	CD 0	4/22/15	4/22/15	0
4	CD 1/2/3A	2/1/17	2/1/17	0
5	CD 3B	8/1/17	8/1/17	0
6	CD 4	7/30/20	7/30/20	0
7	R & D (OPC)	4/22/15	1/18/17	2,000
8	Research and Development	4/22/15	1/18/16	500
9	Research and Development	1/19/16	1/18/17	1,500
10	Construction (TEC)	2/1/17	7/30/20	35,000
11	Laser Systems	2/1/17	12/23/19	14,500
12	Bid and Award	2/1/17	6/30/17	0
13	Production	7/3/17	12/23/19	14,500
14	Ancillary Systems	2/1/17	3/18/20	7,650
15	Opto-Mechanical Systems	2/1/17	3/18/20	5,250
16	O-M System Design	2/1/17	9/26/17	750
17	O-M System Production	9/27/17	3/18/20	4,500
18	Electronics & Contorls	2/1/17	3/18/20	2,400
19	E&C Design	2/1/17	9/26/17	600
20	E&C Production	9/27/17	3/18/20	1,800
21	Conventional Facilities	2/1/17	1/31/20	8,000
22	Design	2/1/17	1/31/18	2,000
23	Construction	2/1/18	1/31/20	6,000
24	Site & System Integration	2/1/17	11/5/19	1,850
25	Planning & Config	2/1/17	1/29/19	200
26	Outfitting	1/30/19	11/5/19	400
27	Intallation & Integration	1/30/19	11/5/19	1,250
28	Project Management	2/1/17	7/30/20	3,000



- Preliminary estimate is ~$35 M with 40% contingency
- Project to be preceded by 2 yr R&D phase to validate base technology
- Schedule
  - CD0 in Q3 of FY15
  - CD1/2/3a in Q2 of FY17
  - CD4 in Q3 of FY20
- Operating cost for k-BELLA : estimated at $3.5 M/yr (note: BELLA ops $2.5M in FY15)

For k-BELLA, revolutionary new laser technology will be required and a path is emerging

State-of-the-art:



Ti:sapphire

40J, 40fs, 1Hz

Yb fiber

50kW, 30% eff., CW

Yb fiber

100kHz, 45fs, 1mJ

Upgrade path:

Higher reprate, efficiency

Short pulses

Higher energy, efficiency

Goal:

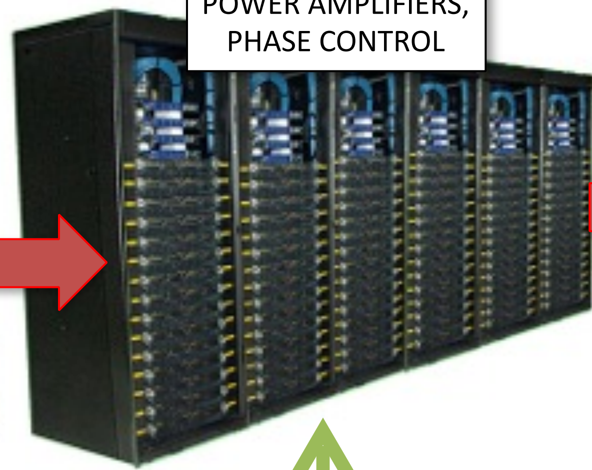
3J
100fs
3kW
20% eff.
1kHz

A 3kW LPA driver would get energy from a fiber amplifier array

PULSE GENERATION, MODULATION

POWER AMPLIFIERS, PHASE CONTROL

COHERENT COMBINATION, RECOMPRESSION

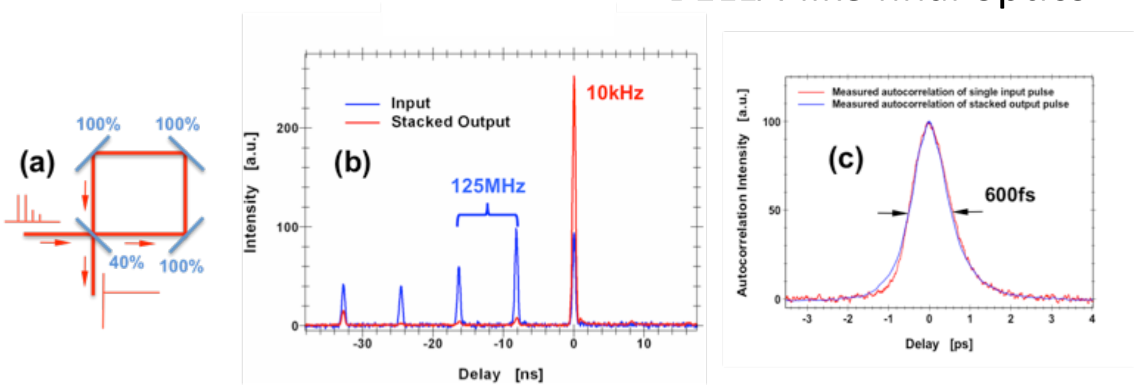


OUTPUT

Low average power, current technology

Custom amplifiers from industry

New combiner technology, BELLA-like final optics



Advertisement 1

We are planning a workshop on R&D Roadmap for Future Plasma Based Colliders

What: develop a roadmap for the R&D that addresses critical questions for a plasma based collider. The collider can either be laser or particle beam driven. Get leaders in the field together (proponents and critics) for a comprehensive plan that has well managed expectations and has broad community buy-in. Identify the needed resources to execute the roadmap.

Who: LBNL (BELLA/LOASIS scientists), SLAC (FACET scientists), BNL (ATF), ANL (AWA), FNAL (critics), UCLA, UT Austin, U Maryland, U Michigan, LLNL,… European labs (DESY, CERN, JAI, CEA, CNRS, INFN), Include also scientists and engineers that have expertise and experience in estimating technical systems and requirements.

Where: Granlibakken (Tahoe, CA) (?)

When: Winter or Spring 2015 (?)

Will coordinate with EUPRAXIA

Summary

- Colliders are a daunting challenge (for any technology)

Advanced accelerators based on laser plasma concepts continue to reach new achievement milestones: transformational bold approach à la P5! US was the birth place and continues to provide leadership but that is at risk.

- Near term applications are plentiful in non-HEP and allow HEP to be steward. But shorter term HEP applications are also emerging: detector test facility, 3 GeV secondary beam for g-2 experiment (idea of Lebedev et al., FNAL),…

- We are moving rapidly along the development S-curve. Need to make LPAs work every day to enable applications
- Investments are needed:
  - R&D in LPA and in plasma sources (much like for RF cavities)
  - High average power laser drivers (much like RF power sources)
    - Laser technology rapidly evolving—driven by industry
    - We want to build k-BELLA: it pushes the next frontier!
  - Rapid high fidelity simulation tools and theory support
  - Provide opportunities for students and postdocs in this exciting field

Logistics of LBNL Laboratory Tours
August 30, 2014, Saturday

11:00 am bus arrives to LBNL – Bldg. 71 Parking Lot

11:00 – 11:05 forming three groups to visit the labs: 2 Laser Plasma Accelerator (LPA) Labs - and the LBNL Magnet Program areas in a rotating fashion. Further subdivison or focusing only to one area is also possible, depending on the number of people interested in each places.

11:05 – 11:30 Rotation #1 (Group1–LPA LabA / Group2–LPA LabB / Group3–Magnet Labs)

11:30 – 11:35 all walk to next Rotation location

11:35 – 12:00 Rotation #2 (Group2–LPA LabA / Group3–LPA LabB / Group1–Magnet Labs)

12:00 – 12:05 all walk to next Rotation location

12:05 – 12:30 Rotation #3 (Group3–LPA LabA / Group1–LPA LabB / Group2–Magnet Labs)

12:30 – all walk to lunch room, Bldg. 71 Conference Room #264

Laboratory Locations:

LPA Labs: A – LPA Staging and Undulator Experiments - Bldg. 71 Center, Cave A
LPA Labs: B – LPA BELLA Laser and Experiments - Bldg. 71 West, BELLA

Magnets: 1 – LBNL Magnet Program - Bldg. 46
Magnets: 2 – LBNL Magnet Program - Bldg. 77 (if we have cars)

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Conclusion

- LPAs advantageous as light source (synchronization, hyper-spectral, compact, economic, few-fs, high peak-power)

- Efforts underway: higher rep rate, controlled injection & stable LPAs

- Big global push for LPA-driven X-ray light source: incoherent & FEL

- At LOASIS/BELLA, individual components addressed (undulator, quadrupoles, MW seed at the 15th harmonic)

- Currently: LPA injection & acceleration
- Currently: Seed optimization
- Future: Upgrade e-beam transport
- Future: X-ray light source